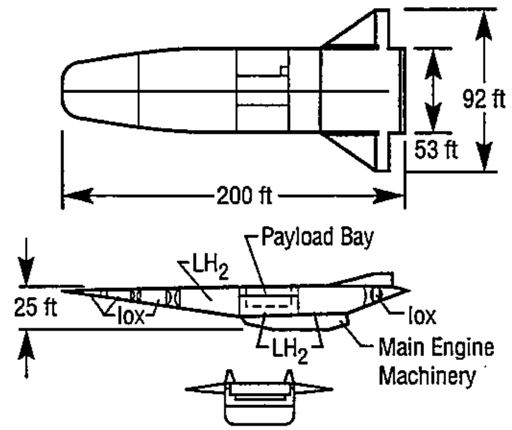
The air-breathing/rocket-powered single-stage-to-orbit configuration is designed to take off horizontally and land horizontally. The baseline propulsion system is derived from that being developed by the National Aerospace Plane (NASP) Program. The reference vehicle uses a special low-speed propulsion mode, ramjets, and supersonic combustion ramjets (scramjets) for primary propulsion along with lox/$LH_2$ rocket augmentation in the low and high speed regimes of the ascent trajectory. The reference vehicle has a gross lift-off mass of approximately 900,000pounds and a dry mass of approximately 240,000 pounds. This concept is illustrated in figure 28.




| Payload* | Final Orbit |
|---|---|
| 25k lb | Station: 220 nmi circ at 51.6° |
| 52k lb | 100 nmi circ at 28.5° |
| 32k lb | 220 nmi circ at 28.5° |
| 14k lb | 100 nmi circ at 90° |

*Includes payload and ASE

Notes:
- Horizontal takeoff/horizontal landing
- 15 percent dry weight margin
- Option for carrying two on-orbit operations crew for 7 days
- Option for carrying four S.S. *Freedom* rotation crew in payload bay
- Option for carrying high energy transfer stage for Atlas-class GEO missions

**Vehicle:**

| | |
|---|---|
| GLOW: | 917k lb |
| Dry Mass: | 239k lb |
| Propellant Type: | Lox/$LH_2$ |
| Main Engine Type: | Air-breather/Rocket |
| Aux. Engine Type/No.: | IME lox/$LH_2$ pump fed/1 |
| Vac Thrust (ea): | 300k lb |
| Vac ISP: | 456 s |
| Area Ratio: | 150 |
| Cryo Tanks: | Gr-Ep $LH_2$/Al-Li lox |
| Primary Structure: | Gr-Ep |
| Control Surfaces: | TMC/ACC |
| TPS: | FRCI–12/TABI |
| Payload Bay—Usable Volume: | 15 ft × 15 ft × 30 ft |

**Figure 28.—Single-stage-to-orbit (air-breather/rocket) vehicle characteristics.**

The cost estimates are given in table 4.

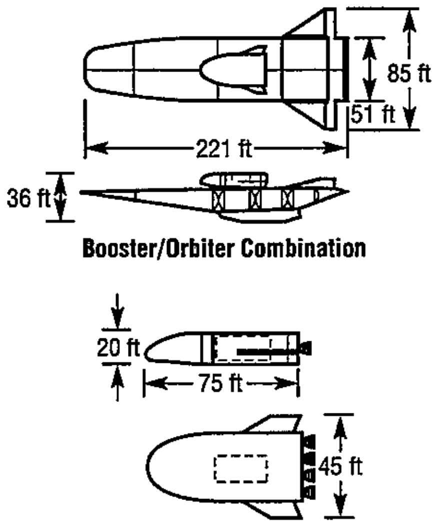
**Table 4.—*Cost estimates for the single-stage-to-orbit air-breather/rocket***

| | FY94 $B |
|---|---|
| Technology | 3.10 |
| DDT&E | 22.0 |
| Annual Operations* | 1.5 |

* SSTO vehicle and associated elements only

### Two-Stage-to-Orbit—Air-Breather/Rocket Combination

The air-breather/rocket-powered two-stage-to-orbit configuration is designed to take off horizontally and land horizontally. The vehicle configuration consists of a booster vehicle and a piggyback orbiter vehicle. The booster propulsion system is a combination of turbofan jet engines and $LH_2$ fueled ramjets. The booster/orbiter staging velocity occurs at Mach 5. The orbiter is powered by four RL–200 class of rocket engines. The reference vehicle has a combined gross liftoff mass of approximately 800,000 pounds and a dry mass of approximately 250,000 pounds. This concept is illustrated in figure 29.




| Payload* | Final Orbit |
|---|---|
| 25k lb | Station: 220 nmi circ at 51.6° |
| 32k lb | 100 nmi circ at 28.5° |
| 31k lb | 220 nmi circ at 28.5° |
| 24k lb | 100 nmi circ at 90° |

*Includes payload and ASE.

| | |
|---|---|
| GLOW: | 802k lb |
| **Booster:** | |
| Dry Mass: | 252k lb |
| Propellant Mass: | 95k lb |
| Propellant Type: | $LH_2$ |
| Engine Type/No.: | Turbofan/Ramjet |
| $LH_2$ Cryo Tank: | Gr-Ep |
| Primary Structure: | Gr-Ep |
| Control Surfaces: | Ti H/C |
| TPS: | TABI |
| **Orbiter:** | |
| Dry Mass: | 52k lb |
| Propellant Mass: | 367k lb |
| Propellant Type: | Lox/$LH_2$ |
| Main Rocket Engine Type/No.: | Expander Cycle/4 |
| T/W: | 54 |
| Vac ISP: | 446 |
| Cryo Tanks: | Gr-Ep $LH_2$/Al-Li lox |
| Primary Structure: | Gr-Ep |
| Control Surfaces: | ACC |
| TPS: | TABI/TUFI |
| Payload Bay—Usable Volume: | 15 ft D × 30 ft L |

Notes:
- Horizontal takeoff/horizontal landing
- Orbiter staged at M = 5
- 15 percent dry weight margin
- Option for carrying two on-orbit operations crew for 7 days
- Option for carrying four S.S. *Freedom* rotation crew in payload bay
- Option for carrying high energy transfer stage for Atlas-class GEO missions

Figure 29.—Two-stage-to-orbit (air-breather/rocket) vehicle characteristics.

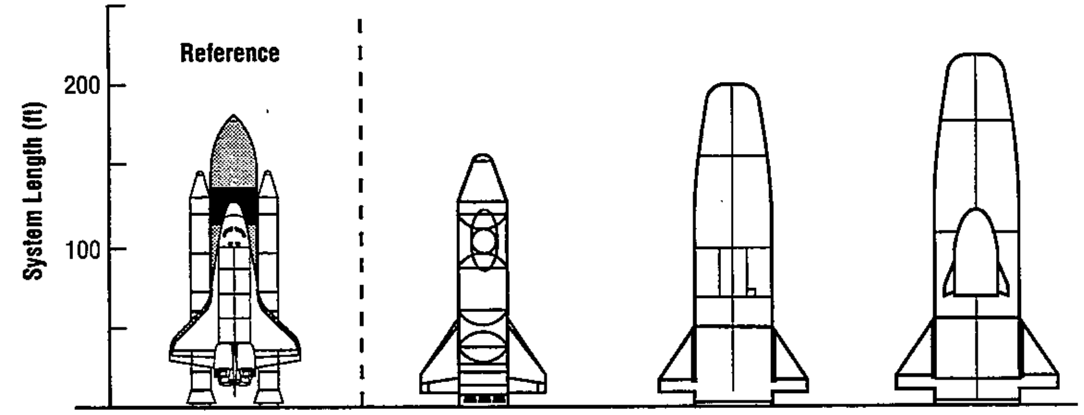
The cost estimates are shown in table 5.

Table 5.—*Cost estimates for the two-stage-to-orbit air-breather/rocket*

| | FY94 $B |
|---|---|
| Technology | 1.20 |
| DDT&E | 26.80 |
| Annual Operations* | 1.45 |

* SSTO vehicle and associated elements only

Key features of each vehicle are shown in table 1 and in figure 30 to allow direct comparison of the alternatives. These vehicles are representative of the concepts and none can be called an optimized design.




| Vehicle | Shuttle | Single-Stage Vehicle | Single-Stage Vehicle | Two-Stage Vehicle |
|---|---|---|---|---|
| Reusability | Partial | Full | Full | Full |
| Propulsion | Rocket | Rocket | Air-breather/Rocket | Air-breather/Rocket |
| GLOW | 4.5M lb | 1.96M lb | 917k lb | 802k lb |
| Dry Weight | 508k lb | 159k lb | 239k lb | 304k lb |
| Payload to 100 nmi circ at 28.5° | 53.8k lb | 41k lb | 52k lb | 32k lb |
| Payload to 220 nmi circ at 51.6° | 25k lb | 25k lb | 25k lb | 25k lb |
| Weight Growth Margin | — | 15% | 15% | 15% |

FIGURE 30.—Option 3: representative vehicle concepts.

## Assessment and Down-Select

All three vehicle concepts evaluated meet the payload delivery requirements set forth at the outset of the study. While the annual operations cost estimates are not a discriminator between the three options, there is a significant difference in the technology and development costs. Neither crew safety, vehicle reliability, impacts to the environment, nor degree of contribution to the industrial competitiveness of the nation appear to be discriminating factors between the three options.

While many significant advances in materials and propulsion related technologies have been made in the National Aerospace Plane Program in the past 8 years, several critical items remain to be developed. These include a ramjet/scramjet engine combination, slush hydrogen systems, and actively cooled engine and leading edge panels. This integrated system must also be overlaid on a requirement for an operable system. While the single-stage-to-orbit air-breather/rocket offers some unique capabilities, such as cruise, self-ferry, and offset launch, the combined technology and development cost estimate exceeds \$25B. The high costs and technology requirements make this an unfavorable option for future space access in the 2008 time frame.

The two-stage-to-orbit air-breathing rocket vehicle, while having many of the advantages of the single-stage-to-orbit air-breathing rocket vehicle, does not require the development of a scramjet and actively cooled panels. However, it does require the development of two dissimilar stages. While the two-stage-to-orbit air-breathing rocket has a lower technology cost than the single-stage-to-orbit air-breathing rocket (i.e., $1.2B), the technology and development cost estimate is $28B. The reduced technology requirements for the two-stage concept do not appear to offset the high development costs of this concept.

Therefore, the development of a single-stage-to-orbit all-rocket vehicle appears to be the best blend of near-term achievable technology and affordability for routine space access beginning in the 2008 time frame. Its combined technology and development cost is the lowest of the alternatives, projected at $17.6–$18.5B. It is an evolutionary, not revolutionary, path that relies on technologies mostly evolved over the past 20 years in the aerospace industry. However, it does require the maturation and demonstration of several key technologies. This is expected to require $900M over 5 years.

The initial single-stage-to-orbit all rocket reference concept, carried throughout the majority of the study, was based on seven Space Shuttle main engine-evolved engines. However, the use of a tripropellant engine (of the RD–704 class) provides for a significant reduction in overall vehicle dry mass (e.g., reduced development cost), as illustrated in figures 27 and 30. At the design reference point of 15 percent dry mass margin, the tripropellant vehicle dry mass is 32 percent lighter than the lox/$LH_2$ vehicle. Because of the requirement for a third propellant tank (i.e., RP), the tripropellant option also allows for a longitudinal, 15-foot diameter by 45-foot long cargo bay to be placed in the vehicle to meet Titan IV payload requirements. The addition of a third propellant (RP) does not appear to significantly affect the cost of operating the single-stage-to-orbit vehicle.

Because of the reduction in vehicle dry mass that allows the vehicle dry weight growth margin to be increased to 25–35 percent, reduced cost, and the potential for meeting Titan IV payload requirements, it is recommended that future studies focus on the development of a single-stage-to-orbit all-rocket vehicle based on a tripropellant engine of the RD–704 performance class.

## Details of Selected Architecture

The propulsion system for the reference vehicle is based on the Russian tripropellant RD–704 engine.

The single-stage-to-orbit all-rocket vehicle is a vertical take-off, horizontal landing, winged concept with a circular cross-section fuselage for structural efficiency. The payload bay is located between an aft $LH_2$ tank and a forward lox tank. The normal boiling point $LH_2$ and lox propellants are contained in integral, reusable cryogenic tanks constructed of aluminum-lithium material. An option exists to construct the fuel tanks of graphite-composite materials for extra margin. The capability for carrying a crew on missions that require human presence is provided by a crew module which is interchangable with the cargo module, but the vehicle remains totally automated. The vehicle employs wing tip fin controllers for directional control. A standardized payload canister concept is used with common interfaces that allow off-line processing of payloads and rapid payload integration.

All nonpressurized primary structural materials are graphite composite, drawing on current airplane and rocket designs. The thermal protection system is composed of advanced carbon-carbon materials for the control surfaces, nose cap, and wing leading edge. The remaining areas of the wing and body are covered with advanced fully reusable surface insulation (AFRSI) where ascent/entry stagnation temperatures will be below 1,200 °F, or TABI where stagnation temperatures will be below 2,000 °F. Both AFRSI and TABI are blanket-type.

The main propulsion system for the single-stage-to-orbit all-rocket vehicle consists of seven tripropellant engines based on the RD–704 engine concept. Specifically, this is a truncated, single–bell version of the RD–701. An alternative is to use three RD–701 engines, each with double bell. The design of the RD–701 is 80 percent complete, with drawings released for all but the main injector, preburner injector, and $LH_2$ turbopump. If selected, the RD–704 design responsibility is to be shared between NPO Energomash (Russia) and Pratt and Whitney. The RD–704 has a component design heritage from the RD–170, RD–120, XLR–129, and Space Shuttle Main Engine alternative turbopump development. The RD–704 engine specifications are given in table 6.

TABLE 6.—*Engine specifications for the RD–704*

| | Mode | 1 | 2 | | Mode | 1 | 2 |
|---|---|---|---|---|---|---|---|
| • Propellants | | $LO_2/LH_2/RP-1$ | $LO_2/LH_2$ | • Chamber Pressure (psia) | | 4,266 | 1,726 |
| • Thrust (lb) | S.L. | 386,140 | N/A | • Area Ratio | | 74 | |
| | Vac. | 441,430 | 175,560 | • Dimensions (in) | Dia. | 70.1 | |
| • Impulse (sec) | S.L. | 356/351 | N/A | (Single Bell) | Length | 151 | |
| (Nominal/Worst Case) | Vac. | 407/401 | 452/450 | • Throttable (percent) | | 10–100 | |
| • Weight (lb) | | 5,300 | | • Total Mass Flow Rate (lb/sec) | | 1,085 | 388 |
| • Mixture Ratio (O/F) | | 4.28 | 6.0 | | | | |

The single-stage-to-orbit all-rocket vehicle is designed to deliver and return 25,000 pounds of payload to the Space Station located in a 220 nautical miles circular orbit inclined at 51.6 degrees. In addition, the design includes enough additional propellant to provide a 5-minute launch window for Space Station rendezvous.

One major design issue is to provide for a safe recovery of the vehicle in the event of a loss of the thrust from one engine throughout ascent. The single-stage-to-orbit all-rocket vehicle meets this mission requirement by providing for the capability to return to the launch site in the event of the loss of an engine from lift-off to 206 seconds into the trajectory. The vehicle can fail-safe abort to orbit with a loss of one engine beginning at 40 seconds, and can fail-operational abort to orbit beginning at 190 seconds. Thus, a 166-second overlap exists between the two major abort modes. A return-to-launch-site analysis was also performed assuming that a 50 feet per second (fps) headwind existed (50 fps wind blowing in the direction of the launch azimuth). This wind profile only reduced the overlap by 1 second because most of the abort flight profile occurs at low dynamic pressures. Note that the single-stage-to-orbit all-rocket vehicle does not require any downrange abort sites to support this abort capability. Multiple engine-out aborts were also analyzed. This analysis was performed for the lox/$LH_2$ vehicle, but results should be similar for the tripropellant options (with the same number of engines).

The entry trajectory of the single-stage-to-orbit all-rocket vehicle is designed to not exceed the temperature capability of the thermal protection system, to not exceed a total acceleration of 1.5 G's, and to provide a cross-range capability in excess of 1,100 nautical miles. The entry thermal environment of the single-stage-to-orbit all rocket is less severe than that of the Space Shuttle. The strategy is to design deorbit targets that will result in the vehicle having a desired energy state and attitude at entry interface to allow heat rate and cross-range control during atmospheric entry. Modulation of the vehicle's bank angle and angle of attack during entry will provide control of both heat rate and cross-range capability. A sufficient control margin exists to allow the center of gravity of the payload to be anywhere along the longitudinal axis of the payload bay on the single-stage-to-orbit all-rocket vehicle.

## Single-Stage-to-Orbit Feasibility

Single-stage-to-orbit rockets have long been known to be highly desirable, but their feasibility has always been questioned on margin and mass-fraction grounds. An analysis was performed to illustrate the effects of advancing technology on the assessment of the single-stage-to-orbit all rocket feasibility.

The propellant mass faction, both required and achievable, is shown in figure31 for three time frames. It is seen that whereas practical-sized vehicles were not attainable until a few years ago, technology that could be matured in the next several years would reverse that conclusion, yielding a larger mass fraction than required.

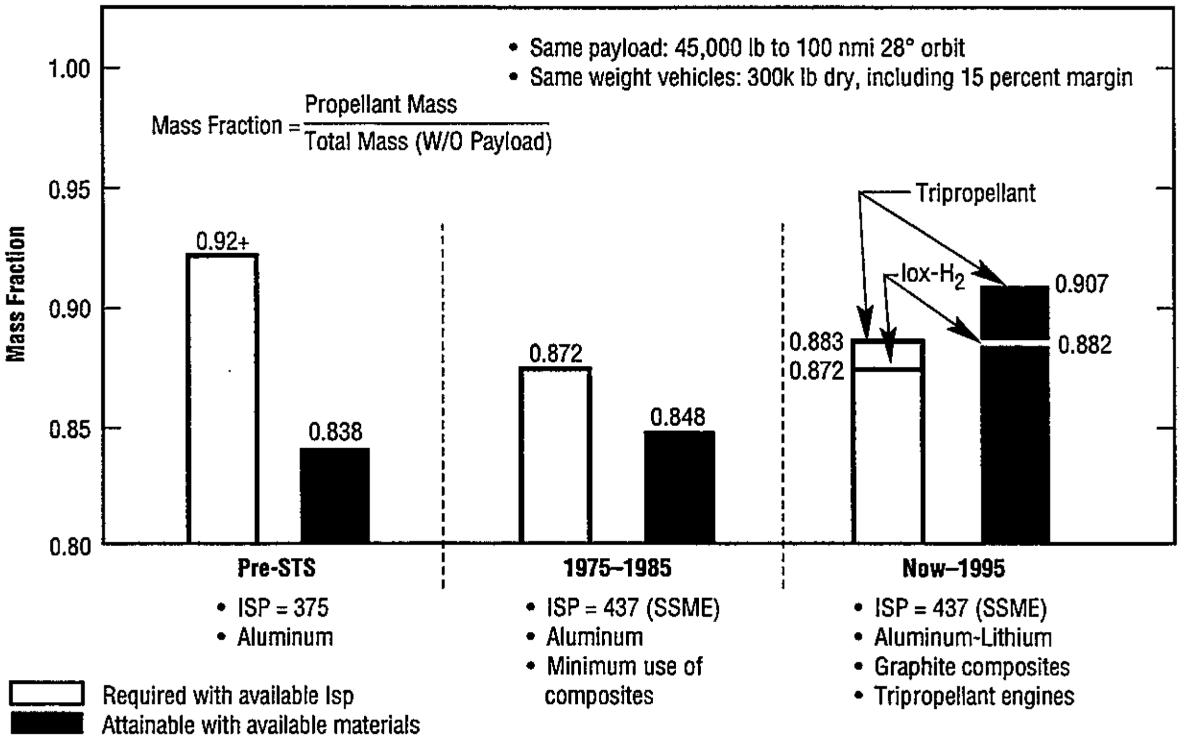



**FIGURE 31.—Single-stage-to-orbit rocket vehicle mass fraction (for practical-sized vehicles).**

This excess available mass fraction manifests itself in dry weight growth margin, with the bars of figure32 indicating that the adoption of increasingly advanced technologies, proceeding cumulatively from left to right, shows rapidly increasing growth margin in the vehicle. Thus a single-stage-to-orbit vehicle that was infeasible using Space Transportation System (STS)-level technologies would allow dry weight to grow up to 31 percent without impacting the payload at all if the advanced technologies identified in this section are implemented. The existence of such a large margin indicates that development of single-stage-to-orbit vehicles can be considered with confidence once these technologies are matured and demonstrated.

It should be emphasized at this point that the reference single-stage-to-orbit all-rocket vehicle is not a maximum technology design. It uses Al-Li cryo tanks, composite structures, and tripropellant propulsion. The substitution of graphite-composite materials in the fuel tanks shows a large benefit and thus should be considered for this vehicle. In addition, there exist many advanced technologies that could offer the potential for an improved design, either in terms of performance or reliability, maintainability, and operability. These include new lightweight propulsion systems, multiposition nozzles, hot structures, conformal cryogenic tanks, low-pressure or pressure-stabilized cryogenic tanks, and use of slush hydrogen propellant. However, none of these latter technologies are considered sufficiently mature to include in a vehicle or in a near-term technology plan at this time.

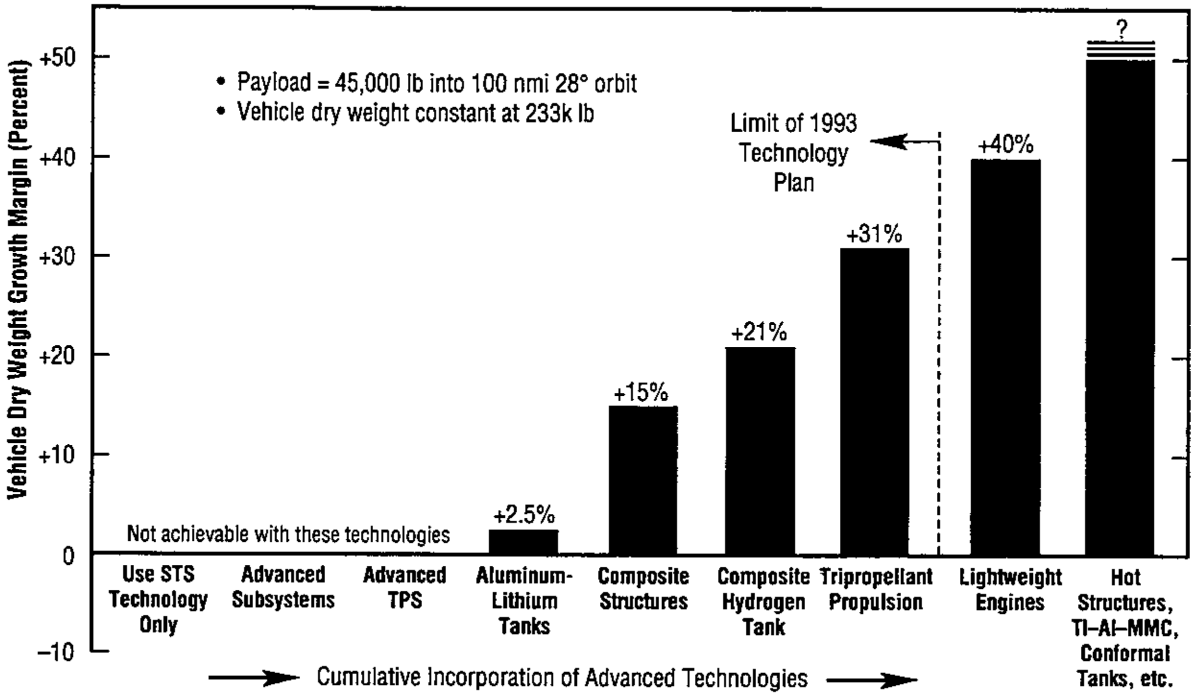



FIGURE 32.—Weight growth margin available.

## Operations Plan

Three fundamental approaches are evident in every modern aerospace endeavor, and all are equally important for a truly efficient launch capability:

- Design-in modern technology that can deliver a simpler vehicle
  - Design-out complex, less operable elements and subsystems (stages, hypergolics, ground support equipment, etc.)
  - Design-in operability (subsystem access, vehicle health monitoring (VHM), etc.).
- Eliminate flight-by-flight vehicle detailed inspection (almost a certification)
  - Proper margins proven in prototype testing
  - Confidence in subsystem status via vehicle health monitoring
  - Perform major overhauls and inspections in regularly scheduled depot maintenance periods (maintenance only by exception between flights).
- Manage for operations
  - Empower individuals to conduct full flight operations (program manager, crew chief, and flight manager)
  - Separate development from operations (3:1 staffing ratio, reduced sustaining engineering).

These philosophies and technologies will lead to a launch capability with fewer facilities, far fewer people, fewer unique tools, and much lower costs. A program that capitalizes on these benchmarks can dramatically reduce the infrastructure and, therefore, the costs associated with space launch. Under these philosophies, analyses of ground processing and flight operations have shown a reduction in the complexity of operations, facilities, and staffing required to conduct space launches. Operability is designed in from the start of the program.

### Ground Operations

Analysis indicates that using these operations philosophies, the single-stage-to-orbit all-rocket vehicle can deliver space launch capabilities with dramatically reduced operations costs. The single-stage-to-orbit all-rocket vehicle has eliminated Space Shuttle vehicle elements and associated Kennedy Space Center facilities and specialized support equipment. Well-established flight margins and a comprehensive vehicle health monitoring system will provide reduced pre- and post-flight testing requirements. These changes will reduce the dedicated Kennedy Space Center workforce requirements by 1,100 people. Coupled with a reduction in personnel support overhead (nontouch-to-touch labor ratio), reductions in Kennedy Space Center ground processing costs of up to 55 percent can be realized. Launch complex 39A or B will be modified to allow for single-stage-to-orbit launch. The vehicle will be processed in a hangar in the horizontal position, moved to the launch pad via a transporter, and erected to the vertical orientation.

Additionally, significant cost savings at non-KSC facilities are realized by the elimination of Space Shuttle elements: continuing production and shipment of the external tank, production and refurbishment of solid rocket motors, Spacelab, pre-planned product improvement, and other orbiter items (i.e., remote manipulator system). Elimination of these elements will reduce the dedicated workforce requirements by an additional 8,800 people.

### Mission Design and Operations

Similar to ground operations, the costs of mission design and operations can shrink substantially by the incorporation of modern operations technology and philosophies.

The concept of a crew chief will be applied to the mission design and flight operations activities. A team of engineers led by a mission manager will be assigned to each vehicle and given the responsibility for the mission design, definition of mission-unique software parameters, and real-time mission support. Each team will consist of 20–25 engineers with a support team to maintain the operations support center, software verification laboratory, and the required analysis tools and data bases. When necessary, additional systems support will be provided by the vehicle crew chief and ground team or depot maintenance team.

Given the autonomous operations for such areas as vehicle health monitoring, navigation, and targeting, and the use of automatic flight control systems built into the vehicle, the mission design and flight operations functions can be handled with a significantly reduced number of people from the number required by current Shuttle or expendable launch vehicle operations.

### Summary of Development Strategy

Based on focused government and industry surveys, the team has identified a set of desirable program attributes in the areas of management, technology maturation and development, production, operations, and maintenance. These include:

- Goals/objectives established at program start
- Quality and safety as top project priorities
- Strong customer involvement
- Streamlined budgeting/tailored acquisition procedures
- Single program manager with a small, centralized staff
- Small teams of expert staff
- Abbreviated reporting, coordinating, and review
- Limited interface specifications
- Utilize best commercial practices and standards
- Dedicated collocated design and development personnel
- Concurrent engineering
- Prototype approach to vehicle development.

The overall theme of the attributes is that program success is achieved by defining a set of clearly focused goals and requirements at the outset of the program coupled with a small, specially empowered management team. The Option 3 team strongly recommends that any new NASA vehicle program strive to implement as many of the attributes listed as possible, to help ensure program success.

In all cases benchmarked, increased reliability and performance, reduced maintenance requirements, and reduced operations manning are being demonstrated. Advanced technology systems, when designed for operability and operated within a well defined envelope, can be efficient and operated routinely.

### Program Phasing

The fully reusable launch vehicle program will consist of the four phases shown in figure 33. These are: predevelopment, full-scale development, production, and operations. The predevelopment phase of calendar year (CY) 1994 to 2000 will consist of rigorous preliminary design efforts to fully derive requirements and to select critical technologies, implementation of required flight and ground test experiments, and a technology maturation program. In CY97, a decision to pursue new space launch vehicle options will be needed to meet the intended pace of the program. Prior to full-scale development, all technologies must be matured to technology readiness level (TRL) 6. In the CY2000 time frame, the full-scale development phase will start. This will include final design and development coupled with a prototype test program beginning in the CY2004 time frame. The basic philosophy of these two phases is to lower program risk by maturing technologies before full-scale development, to verify the integration of the entire system, and to fully define the operating envelope before the vehicle becomes operational. This requires a series of low-cost, clearly defined small-scale projects that are product oriented and lead up to full-scale development (e.g., ground and flight experiments and experimental (X) vehicles).

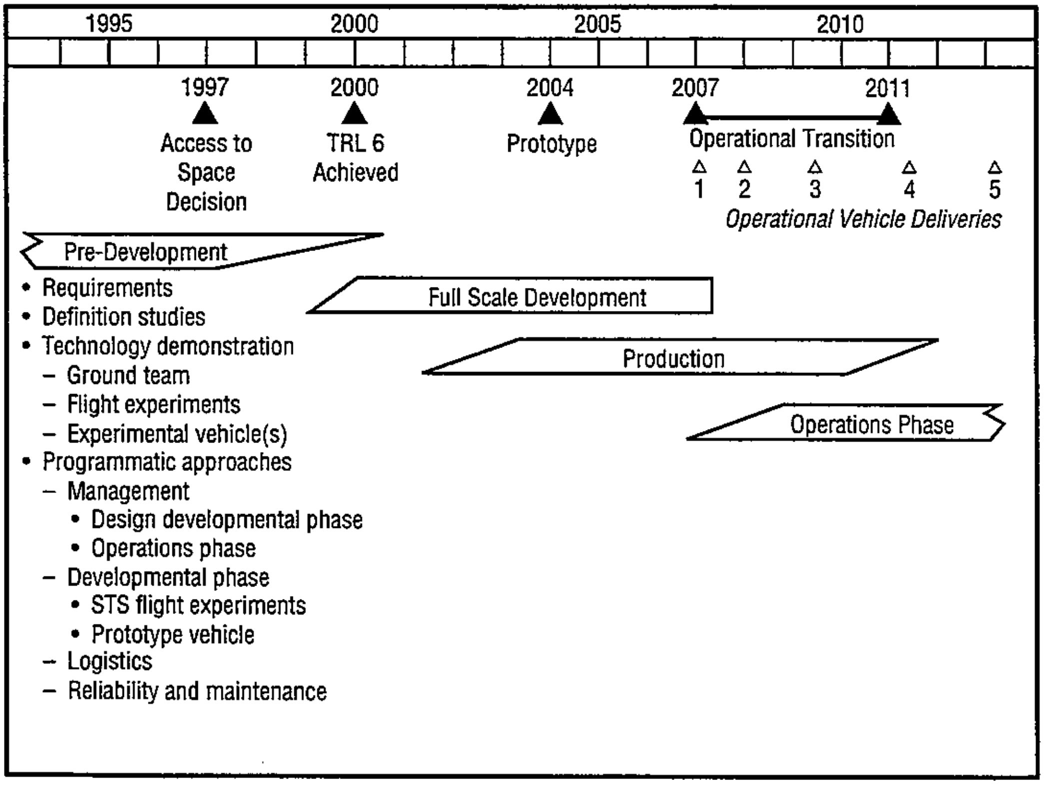



FIGURE 33.—Program phasing.

The production phase will overlap the full-scale development and operations phases. At the end of the development phase, the new vehicle will be turned over to an operating organization. The CY2007 to 2009 time frame will serve to transition operations from the Space Shuttle fleet to the new vehicle fleet. No preplanned product improvements will be pursued. The only changes allowed on the new vehicle will be those required due to a defect or those that can be shown to pay for themselves in a reasonable period.

# Technology Plan

An Agency-wide subteam was established to assess current subsystem technology maturity levels for the three representative vehicle design options. The principal product of this subteam was the documentation of a plan to mature these technologies to a readiness level value of 6 by CY2000. Technology readiness level 6 is defined as "successful system/ subsystem model or prototype demonstration in a relevant environment (ground or space)." The subteam has several working groups that consist of structures and materials, thermal protection system, propulsion, aerosciences, avionics, and operational specialists. The total technology plan was estimated to require $900M over 5 years.

The result is a prioritized plan that identifies both enabling (requisite) and enhancing (upgrading) technologies. A core set of enabling technologies common to all three advanced technology concepts was also identified. These are discussed below.

## Reusable Cryogenic Tanks

A common element of fully reusable vehicles that has not been explored in any depth in prior technology efforts is the development of long life/low maintenance/operable reusable cryogenic tank systems. The cryogenic tank system includes both the tank structure and insulation (both cryogenic and aerothermal). Included in this task are the development of tank certification criteria; nondestructive evaluation (NDE) techniques; establishment of a materials data base; optimization of materials processing and fabrication; the design, fabrication, and analysis of a large-scale cryogenic tank system including structural and thermal cycling; and incorporation of vehicle health monitoring.

## Vehicle Health Management and Monitoring

Vehicle health management and monitoring, while being successfully and widely utilized on high-performance military and commercial aircraft, is not nearly as mature on domestic space launch systems, with the exception of certain subsystems on the Space Shuttle. Application of these existing techniques to launch vehicles permits real-time identification and rectification of vehicle subsystem anomalies. Definition of critical items to be monitored and stored, development of data transfer techniques, "smart" management algorithms, and development of ground processing procedures, including responsive maintenance capabilities, are included in this area.

## Autonomous Flight Control

To achieve low cost space transportation, most in-flight functions must be automated and control responsibility transferred to the vehicle. Autonomous flight control is both possible and near state of the art for ascent, re-entry and landing. On-orbit operations, such as routine rendezvous and docking at the Space Station, are also near state of the art and are under development by NASA. The technology objective is to develop and demonstrate these integrated techniques.

## Operations Enhancement Technologies

The focus on low operations cost approaches for launch systems has resulted in an assessment of operations requirements derived from a series of studies and benchmark evaluations. Several key areas requiring further investigation include: operable and reliable rocket engines, leak-free propellant feed valves and joints, electro-mechanical actuators, and electrohydraulic actuators.